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**14. ABSTRACT**

The goal is to design the Spring Ankle with Regenerative Kinetics (SPARKy) which seeks to develop a new generation of powered prosthetic devices based on the Robotic Tendon actuator. This actuator is a lightweight motor and transmission in series with a helical spring that significantly minimizes the peak power requirement of an electric motor and total system energy. The Robotic Tendon has kinetic advantages and stores and releases energy to provide SPARKy users with 100% of required push-off power and ankle range of motion comparable to able-bodied ankle motion while maintaining a form factor that is portable to the wearer.
The objective is to build a transtibial prosthesis that will support a Military amputee's return to active duty.

**15. SUBJECT TERMS**
Transtibial Prosthesis, regenerative, spring, wearable robot

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# Introduction

### ”SPARKy – Spring Ankle with Regenerative Kinetics” to build a new generation of transtibial prostheses

**Keywords:** Transtibial Prosthesis, regenerative, spring, wearable robot

The goal is to design the *Spring Ankle with Regenerative Kinetics (SPARKy)* which seeks to develop a new generation of powered prosthetic devices based on the Robotic Tendon actuator. This actuator is a lightweight motor and transmission in series with a helical spring that significantly minimizes the peak power requirement of an electric motor and total system energy. The Robotic Tendon has kinetic advantages and stores and releases energy to provide SPARKy users with 100% of required push-off power and ankle range of motion comparable to able-bodied ankle motion while maintaining a form factor that is portable to the wearer.

**Objective:** The SPARKy Team using several unique technologies developed at Arizona State University’s Human Machine Integration Lab will build a new generation of smart, active, energy-storing, transtibial prostheses that will support a Military amputee’s return to active duty.

**Military Relevance:** Military amputees have unique requirements not found in the general amputee population. Military amputees are typically highly active and young. Their profession requires that they perform physically demanding dynamic tasks under severe conditions. Current state-of-the-art devices that are commercially available and in research do not address their unique requirements. SPARKy is the only device of its kind designed to address the technologically challenging requirements of the highly active Military amputees. SPARKy is very powerful and efficient. This will allow the amputee to carry heavy loads while walking at speeds up to 2 m/s. The mechanical design addresses the demanding nature of the service member’s environment and conditions. For example, the complete electronics and power train package can easily be removed in the case of a malfunction in a field condition, so that the device transforms into a conventional prosthesis.

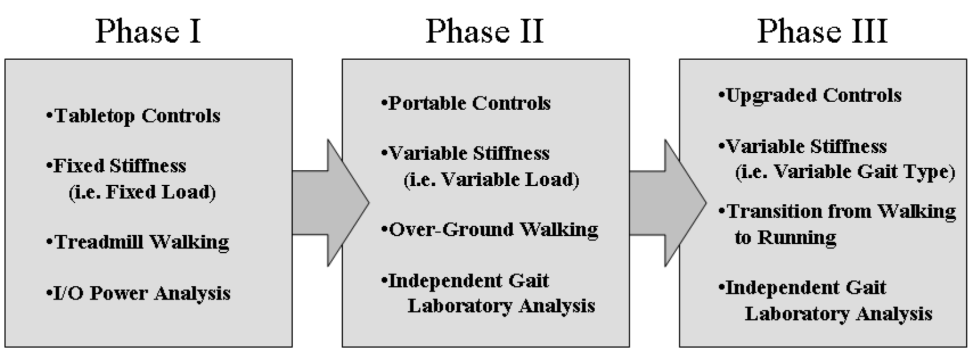
**Public Purpose:** A transtibial prosthetic device that satisfactorily mimics able-bodied gait can be used by the general public. Because of the prevalence of diabetes, the number of below-the- knee amputees will increase greatly. In the first year, we found that the subject’s health improved because he was briskly walking on a treadmill with a powered prosthetic device.

# Body

Even today’s most sophisticated microprocessor controlled foot-ankle prosthetic devices are passive. They lack internal elements that actively generate power, which is required during the “push-off” phase of normal able-bodied walking gait. Amputees must rely upon the limited spring-back available within the flexed elastic elements of their prostheses to provide power and energy and thus must modify their gait through compensation. Consequently, lower limb amputees expend 20-30% more metabolic power to walk at the same speed as able-bodied individuals. A key challenge in development of an active foot-ankle prosthetic device is the lack of good power and energy density in current actuator technology. Human gait requires 250W of peak power and 36 Joules of energy per step (80kg subject at 0.8Hz walking rate). Even a highly efficient motor such as the RE75 by Maxon Precision Motors, Inc. rated for 250W continuous power with an appropriate gearbox would weigh 6.6 Kg. This significant weight is only the actuator and transmission. It does not include the electronics or the batteries.

The goal for Phase 1 is to design the *Spring Ankle with Regenerative Kinetics (SPARKy)* which seeks to develop a new generation of powered prosthetic devices based on the Robotic Tendon actuator. This actuator is a lightweight motor and lead screw in series with a helical spring that significantly minimizes the peak power requirement of an electric motor and total system energy. The kinetic advantages of the Robotic Tendon will be shown along with the electro-mechanical design and analysis that will provide SPARKy users with 100% of required push-off power and ankle range of motion comparable to able-bodied ankle motion while maintaining a form factor that is portable to the wearer.

SPARKy Project Overview



**Phase 1. To develop, test and demonstrate a transtibial prosthesis based on our "Robotic Tendon" technology (Months 1-12):**

a. Design and build SPARKy I with the capability to support walking on a treadmill. Sensor feedback will identify user intent to start, stop and change speed. The device will continue to passively support walking even in the event of battery failure. (Months 1-8).

This subtask has been completed. Sensor feedback allows the user to start, stop and adjust their speed when walking on a treadmill. When power is lost, the pylon is locked in place and the user will walk on the passive carbon fiber keel.

In our design considerations, we kept the passive carbon fiber keel to allow for walking in the event of battery failure.

b. Test and iterate the design with selected transtibial amputees. (Months 9-11).

We have recruited one subject and have tested the design. We are using a harness mounted above the treadmill for safety.

c. Demonstrate SPARKy I to MARP and TATRC. (Month 12).

Completed on November 2nd, 2007 at Brooke Army Medical Center.

**Project Milestones for Phase 1**

| Activity | Duration | Performance Obj |
|---|---|---|
| **1.0 Design, Build, Test and Demonstrate SPARKy I** | **Months 1-12** | Support linear walking, 1 to 2 m/s, on a treadmill. Control scheme will identify user intent to stop, start and adjust speed. Device shows good energy and power savings compared to a direct drive alternative. |
| 1.1 Select, Assemble and Test Prosthesis Componentry (foot/ankle, pylon, socket) for test subjects | **Months 1-2** | Interface a socket and components to a test subject. |
| 1.2 Design, Build and Test Robotic Tendon and Mechanical Interface | **Months 1-4** | Interface with prosthesis. Show DOF using current nut control software/hardware. |
| 1.3 Design, Select, Package and Test Electronic Components | **Months 2-5** | Interface with prosthesis and Robotic Tendon. Show functionality using current nut control software. |
| 1.4 Assemble Hardware | **Month 5** | IAW Hardware Specs/drawings. Supports limb to limb symmetry. |
| 1.5 Design, Develop and Test Control Scheme | **Months 2-6** | Show logical output signal to motor based on sensor input signals. |
| 1.6 Integrate System Hardware, Software and Control. | **Months 7-8** | IAW System Specs. |
| 1.7 System Performance Tests and Iterations | **Months 9-11** | Support linear walking, 1 to 2 m/s, on a treadmill. Control scheme identify user intent to stop, start and adjust speed. Device shows good energy and power savings compared to |

| | | |
|---|---|---|
| | | direct drive alternative. |
| 1.8 System Demonstration | **Month 12** | Using selected Military amputee, show linear walking on a treadmill. Control Scheme identify user intent to start, stop and adjust speed between 1 to 2m/s. |

## Progress for Months 1-12

### Activity 1.1

Prosthesis components were selected. A Freedom FS3000 keel was selected. The keel was modeled in SolidWorks and its stiffness was modeled using a finite element analysis. The model was confirmed using a material testing machine. A standard pylon was used.

Dr. Sugar met with Mark Werner to discuss selecting a subject. Mark Werner looked through his database and then talked with Dr. Sugar. Dr. Sugar followed the guidelines for selecting a subject as outlined in the approved IRB documents.

A subject was selected in May 2007 and the subject signed the consent form.

We received IRB approval from ASU and USAMRMC.

### Activity 1.2

The initial design of the robotic tendon and its interface to the keel was completed on 3/15/2007. Joseph Hitt and Matthew Holgate were in charge of the mechanical design in SolidWorks. Dr. Kevin Hollander consulted on the design of the springs, robotic tendon, and pylon. Parts were machined during the month of March.

Parts were fabricated in April and the device was assembled in May 2007.

Dr. Sugar ordered all the necessary parts for the prosthesis including: keel, pylon, encoders, optical switches, RE40 motor and gearbox, Advantech PC104 computer, and Sensoray 526 board. He met with LiteGait Incorporated to purchase a treadmill based for rehabilitation. A laptop computer was ordered to run Matlab’s control code.

### Activity 1.3

Dr. Sugar, Joseph Hitt, and Dr. Hollander selected electronic components. A plastic case was built to house the electronics. Incremental and absolute encoders were purchased from USDigital.com. Bernardo Bonilla from Robotics Group Inc designed a motor amplifier for the RE40 motor. He investigated the possible use of brushless DC motors for a smaller and more lightweight device.

The control box was assembled in May 2007.

### Activity 1.4

The device was assembled in May 2007 and was tested using a large pole. Joseph Hitt used a large pole to walk the device on the treadmill for initial testing.

**Activity 1.5**
Joseph Hitt has built the controller inside of Matlab. It runs using the xPC Operating system from Matlab. The system allows the user to speed up or slow down automatically as the treadmill speed is varied.

**Activity 1.6**
We integrated the electronics and hardware during the month of May and tested the system.

Bernardo Bonilla from Robotics Group Inc developed a custom electronic PC104 box that houses the batteries, power controller, and electronics. Bernardo packaged the existing electronics in a box that can be worn at the waist.

Figure 1: A PC104, motor amplifier, communication board, fan, and power converter were mounted in a small box to be worn by the user. The batteries are mounted separately from the box.

**Activity 1.7**
Testing was completed during the months of June to December.

**Activity 1.8**
Completed on November 2$^{nd}$, 2007 at Brooke Army Medical Center.

**List of Personnel receiving pay from this research Effort**

1. Thomas Sugar
2. Matthew Holgate
3. Joseph Hitt was not paid by this grant
4. Kevin Hollander, Consultant
5. Bernardo Bonilla, Consultant, Robotics Group, Inc.
6. Mark Werner, Consultant, Arise Prosthetics

**Background Material**

Due to its repetitive nature, the discussion of gait is done in terms of percentages of a gait cycle. A gait cycle is defined for a single leg and begins with the initial contact of the foot with the ground or `heel strike', the conclusion of a cycle occurs as the same foot makes a second `heel strike'. To illustrate a typical pattern of gait, consider the kinematics and kinetics of a normal ankle, see Figures 2 and 3. Notice, the ankle moment (torque) data is normalized by body weight, kg. The gait data is *based on inverse dynamic calculations*.

In figure 2, peak ankle moment occurs at roughly 45% of the gait cycle and at a value of -1.25 Nm/kg or for an 80 kg person, -100 Nm. The negative sign represents the physiological direction for which the moment occurs; in this case, peak moment is acting to move the foot in a toes-down direction. As an interesting note, at the point at which the peak moment occurs, the ankle angle begins a rapid descent to its lowest overall value of -24° at 60% of the gait cycle. The region of gait approximately between 45% and 60% of the gait cycle is known as `push off'. At the conclusion of `push off', now considered `toe off', the leg initiates `swing' and the foot is then positioned for the next `heel strike'.

Use of the term **Robotic Tendon** implies an analogy to human physiology. The simple inclusion of a spring to a linear actuator can provide energy and power savings to the design of a wearable robotic device. The premise is that the human muscular system uses the advantages inherent in its elastic nature. Those advantages are a minimization of both work and peak power. In terms of an electric motor, *minimizing peak power* implies the reduction of requirements for motor size and thus *weight*. Minimizing work implies a *reduction of stored energy* supply or longer battery life.

A conceptual model of the Robotic Tendon can be seen in Figure 4. In the prosthetic system, the forces and displacements are based upon able body ankle gait patterns.

In contrast to a direct drive example, our spring based actuator design has very different characteristics. Using the simple model of the Robotic Tendon in Figure 4, comparisons to direct drive approaches can be seen. In a direct drive approach, the stiffness $K$ can be considered nearly infinite, thus all of the environmental displacements must come from the linear actuator.

From Figure 4, a development of motor power requirements based upon stiffness $K$ can be derived. The position of the environment, $x_g$, is given by converting the joint angles of gait to linear displacement using a simple *lever arm*. The motor position is thus a combination of the position of the environment, $x_g$, and the position of the spring, $x_s$.

Unlike other elastic robot designs, it is important to note that the motor is *position controlled* which is very simple and economical. The position of the motor is adjusted based on the desired gait kinematics and kinetics. The ankle does not interact directly with the motor but interacts directly with the spring. Repeating the previous statement, the motor controls the input side (proximal side) of the spring and the output side (distal side) of the spring is *not controlled*, but moves based on the user.

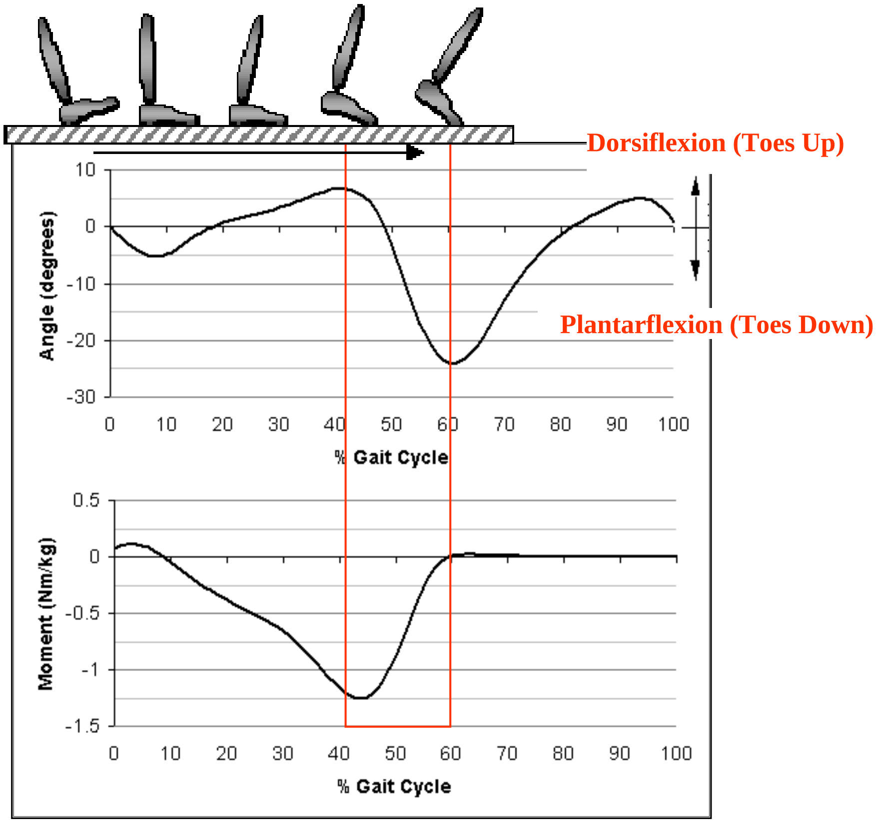



Figure 2: Normal ankle gait kinematics and kinetics.

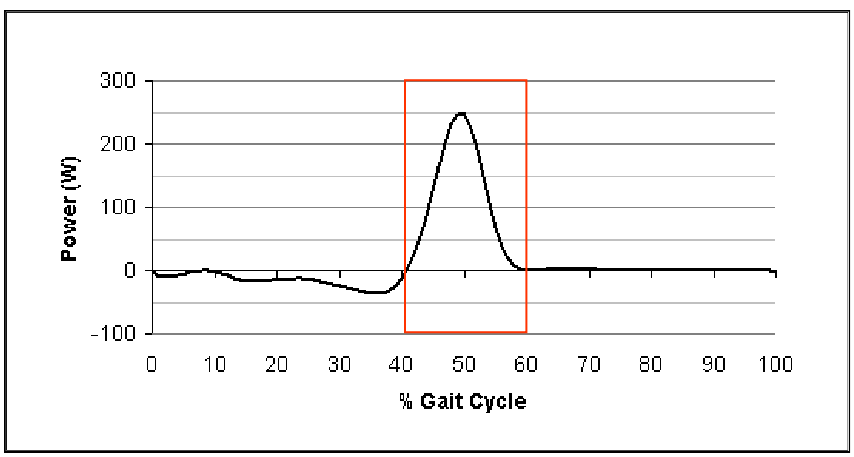



Figure 3: The power during the gait cycle reaches 250W for the following assumptions: 80 kg person, walking at 0.8 Hz (1.25 sec/cycle).

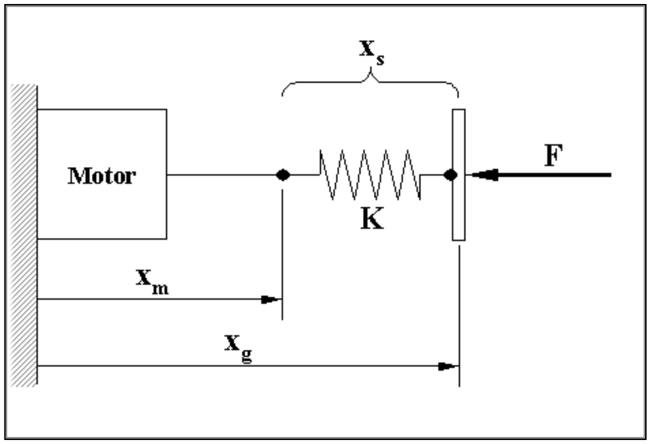


Figure 4: Robotic Tendon Model: A motor and spring in series (spring is tuned for proper gait). We use a position controller to place the spring at the correct location at the correct time. The motor controls the input side of the spring and the output side of the spring is *not controlled*, but moves based on the user.

**Power Analysis**

$$F = K(a_o - x_s)$$

$$x_m = x_g + \frac{F}{K} - a_o$$

$$\left(P_m\right)_{\text{peak}} = \max\left|\underbrace{F \cdot \dot{x}_g}_{\text{gait power}} + \underbrace{\frac{F \cdot \dot{F}}{K}}_{\text{spring power}}\right|$$

Human ankle gait power, $F\dot{x}_g$, can be both negative and positive. When it is negative, a resistance motion is applied to the ankle and when it is positive a propelling motion is applied. A motor unit must provide power, $P_m$, to both resist and propel human motion. For this reason, a direct-drive solution is not energy efficient because the motor is used to resist the motion. Values for force, $F$, velocity, $\dot{x}_g$, and $\dot{F}$ can all be determined from human gait analysis data; thus stiffness, $K$, becomes the only design parameter to reduce the peak motor power.

To design an assistive robotic device for gait, understanding motor velocity and power requirements is fundamental. Consider the case where spring stiffness, $K$, is nearly infinite (i.e. direct drive). In this example the spring power term drops to zero and the motor must provide the absolute value of normal gait power. In the opposite case, consider a spring with stiffness near zero. In the second example, the power requirements tend toward infinity. If we were to assume a straight line between these two cases it would appear that one could never do any better than a direct drive scenario. Fortunately, this simplistic relationship is not the case. On the contrary, if a spring is properly selected both energy and peak power for a motor required to perform human gait can be drastically reduced compared to the direct drive analogy.

**Basic System Principles:**

The operating principles of SPARKy are shown in Figure 5. During the stance phase, the leg rolls over the ankle pulling on the output side (distal side) of the spring. The motor also pulls on the input side (proximal side) of the spring adding stored energy as well. The stored energy is then released quickly during powered plantarflexion.

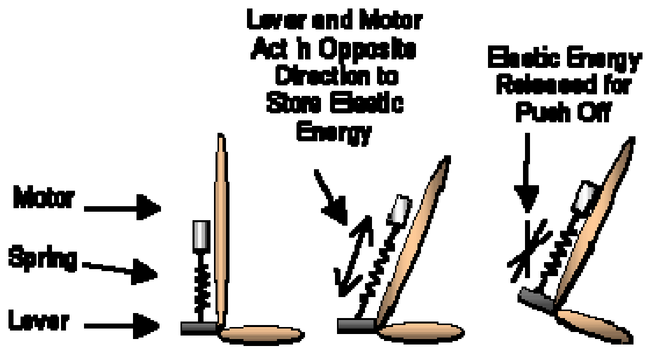


Figure 5: In our prosthetic ankle, the motor and spring are mounted behind the leg. We can then use larger springs to store and release the needed energy. As the leg rolls over the ankle, the motor and lever attached to the keel pull the spring in opposite directions. The stored energy is then released for during powered plantarflexion.

In our design we chose springs because of the following reasons.

- Springs are Powerful
- Springs are Efficient
- Springs are Lightweight
- Springs are Economical
- Springs are Compliant

Our robotic tendon gives us the following benefits.

- Input Power reduced by 2/3
- Weight reduced by a factor of 7
- Input Energy is 1/2 of direct drive example

## SPARKy Design


Figure 6:

1. A Robotic Tendon is mounted behind the leg.
2. Springs are used to store and release energy.
3. Very efficient and lightweight RE40 motor is used.
4. Efficient gearbox and lead screw design.
5. Rod ends are used to quickly adjust the lever arm length.
6. The sensors used include a motor encoder, ankle encoder, and a heel switch.
7. Energy efficient carbon fiber keel is integrated into the device.

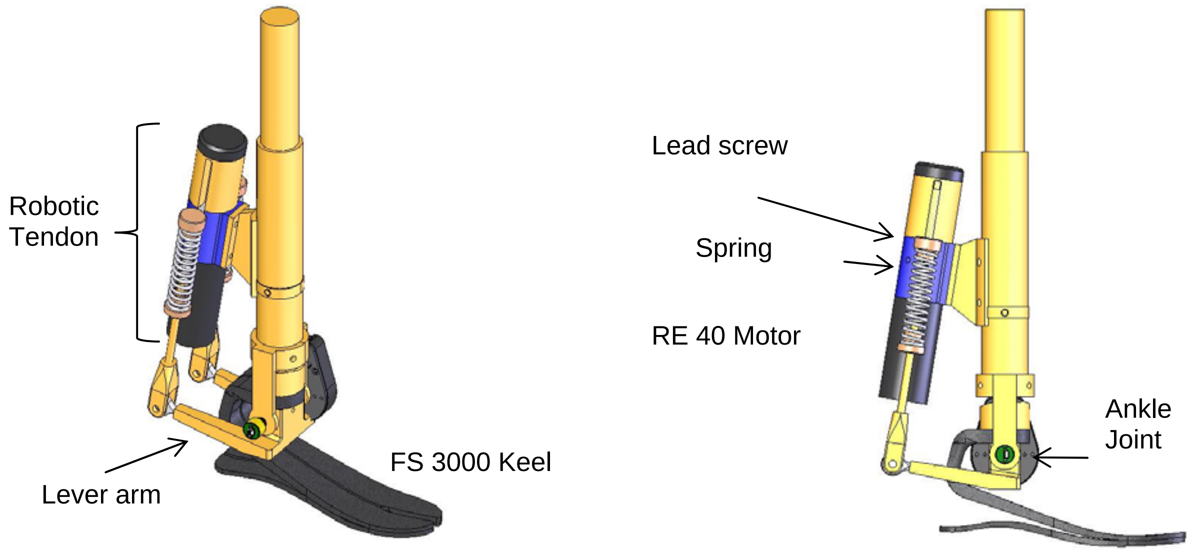



Figure 7: Isometric and side views of SPARKy Phase 1 as modeled in SolidWorks. The Robotic Tendon actuator provides a dynamic moment about the ankle joint.

**Human Subject Data:**

**Our system provides ankle motion that is comparable to able-bodied gait.** See Figure 8.

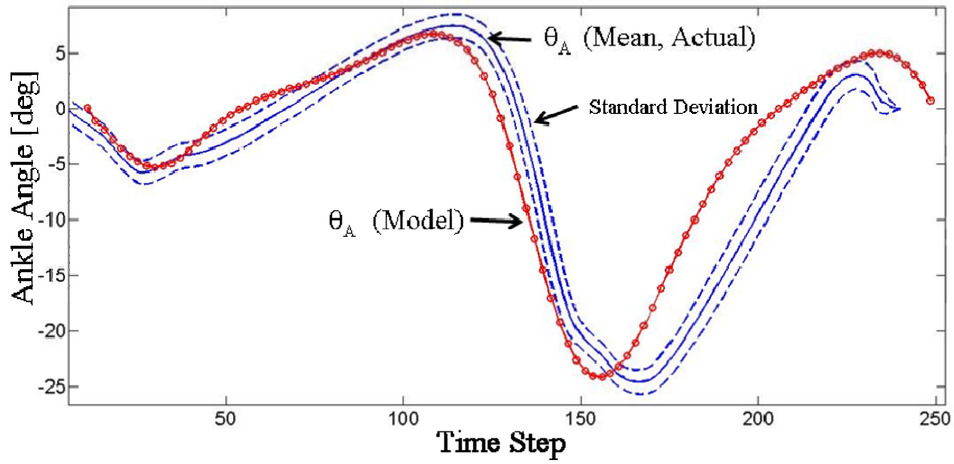



Figure 8: The subject walks on a treadmill at 2.2 mph. The ankle has 9 degrees of dorsiflexion and more importantly 23 degrees of plantarflexion based on the actual lever displacement. The user has complete control of the ankle motion because the output side of the spring is not controlled. The actual lever displacement fits the model extremely well.

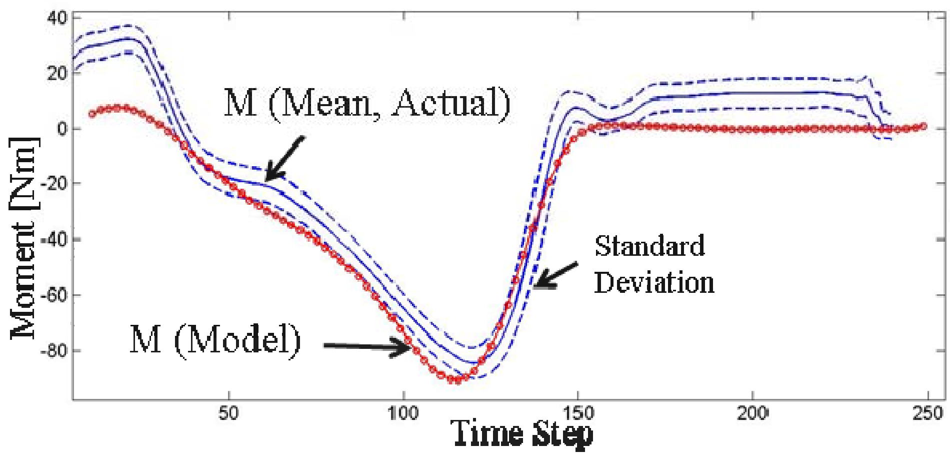



Figure 9: The subject walks on a treadmill at 2.2 mph. The ankle moment matches the model very well.

**Our system provides 100% of required push-off power.** See Figure 10. Our subject requires 250 Watts of push off power, but the motor supplies only 55 watts of power. How is this possible? A power amplification of 4.5 is achieved because the user stores energy in the spring as the leg rolls over the ankle in the stance phase. The motor stores additional energy in the stance phase, and then the spring quickly releases the energy during powered plantarflexion.

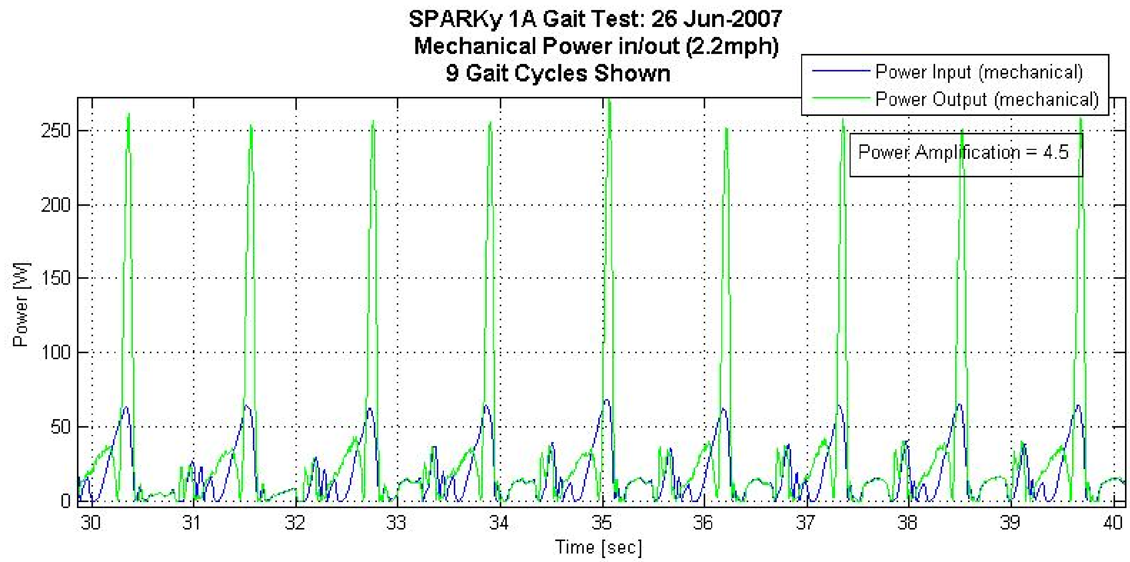



Figure 10: The subject walks on a treadmill at 2.2 mph. At push off, the motor supplies 55 watts of power to the input side of the spring. The output side of the spring supplies 250 watts of power to the subject allowing for powered plantarflexion. This is only possible if the spring stores energy during the stance phase and quickly releases the energy in a powerful burst at push-off.

In Figure 11, the true energy supplied to the device is shown. In real-time, the current and voltage to the motor are measured.

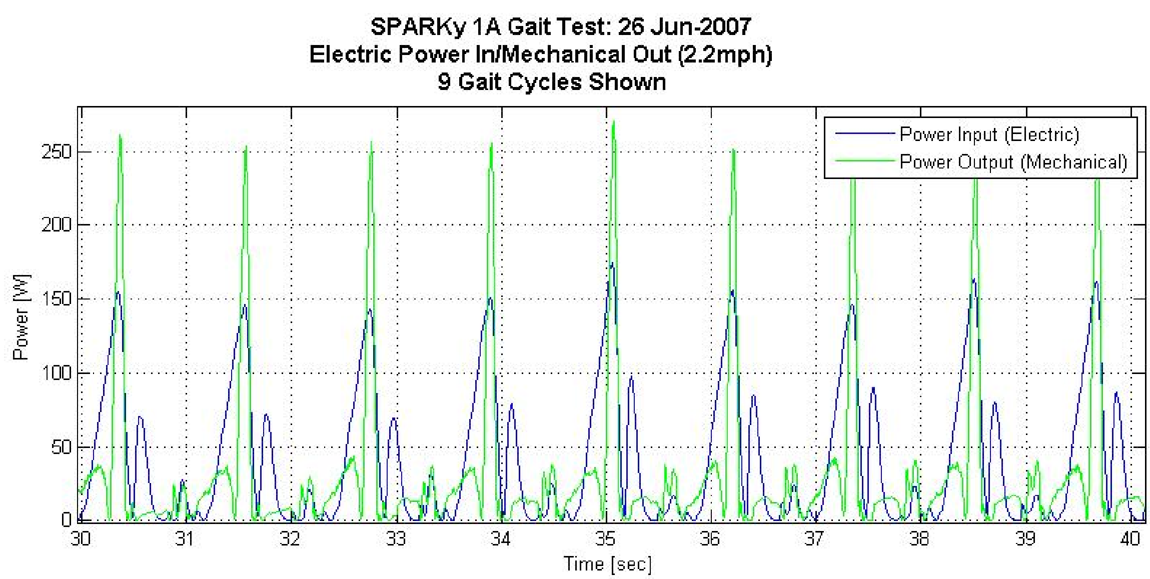



Figure 11: The subject walks on a treadmill at 2.2 mph. At push off, the motor supplies 55 watts of power to the input side of the spring. Because the gearbox, leadscrew, and motor are not perfectly efficient, the electrical input is 150 watts at push off. The output side of the spring supplies 250 watts of power to the subject allowing for powered plantarflexion.

The same data is repeated for the subject walking at 3mph. See Figures 12, and 13.

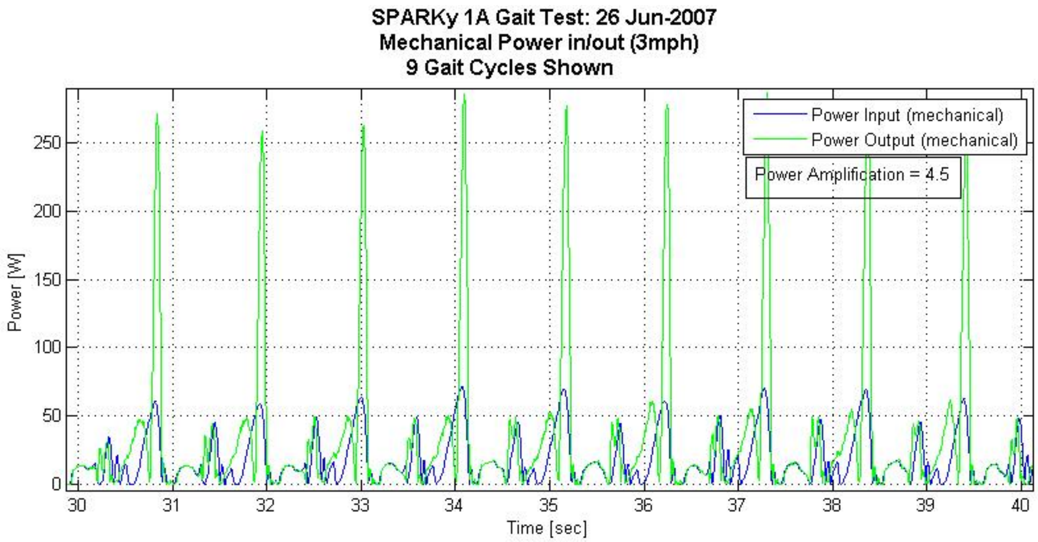



Figure 12: The subject walks on a treadmill at 3 mph. At push off, the motor supplies 60 watts of power to the input side of the spring. The output side of the spring supplies 270 watts of power to the subject allowing for powered plantarflexion. This is only possible if the spring stores energy during the stance phase and quickly releases the energy in a powerful burst at push-off.

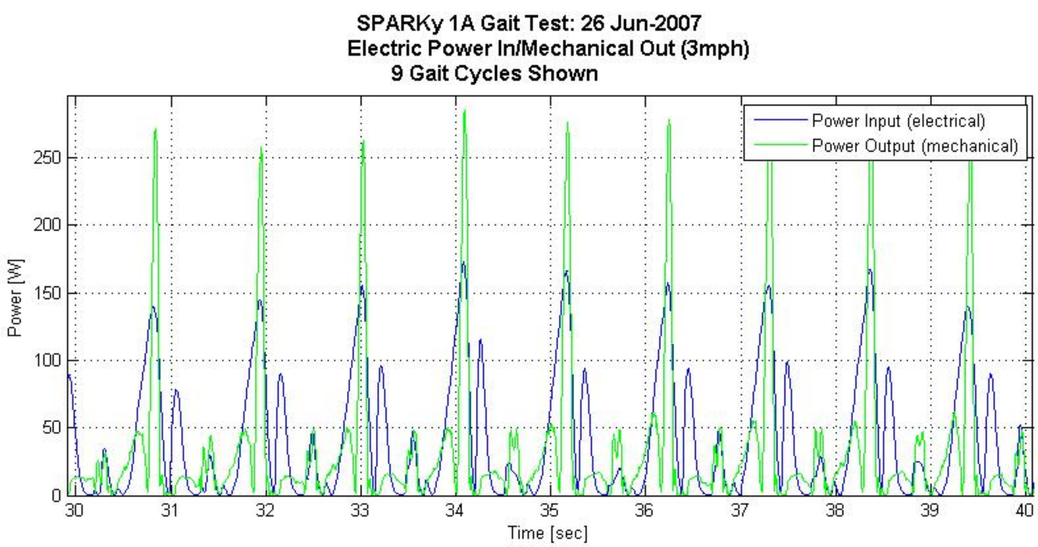



Figure 13: The subject walks on a treadmill at 3 mph. At push off, the motor supplies 60 watts of power to the input side of the spring. Because the gearbox, leadscrew, and motor are not perfectly efficient, the electrical input is 150-160 watts at push off. The output side of the spring supplies 270 watts of power to the subject allowing for powered plantarflexion.

In Figure 14, multiple gait cycles are averaged together. The peak of the mean output power curve is compared to the peak of the main motor input power curve and a power amplification of 3.7 was determined. A sophisticated model of the Robotic Tendon that includes motor inertia, gearbox dynamics, friction, and lead screw dynamics was created. Using this derived model, an output power curve and a motor power curve were simulated.

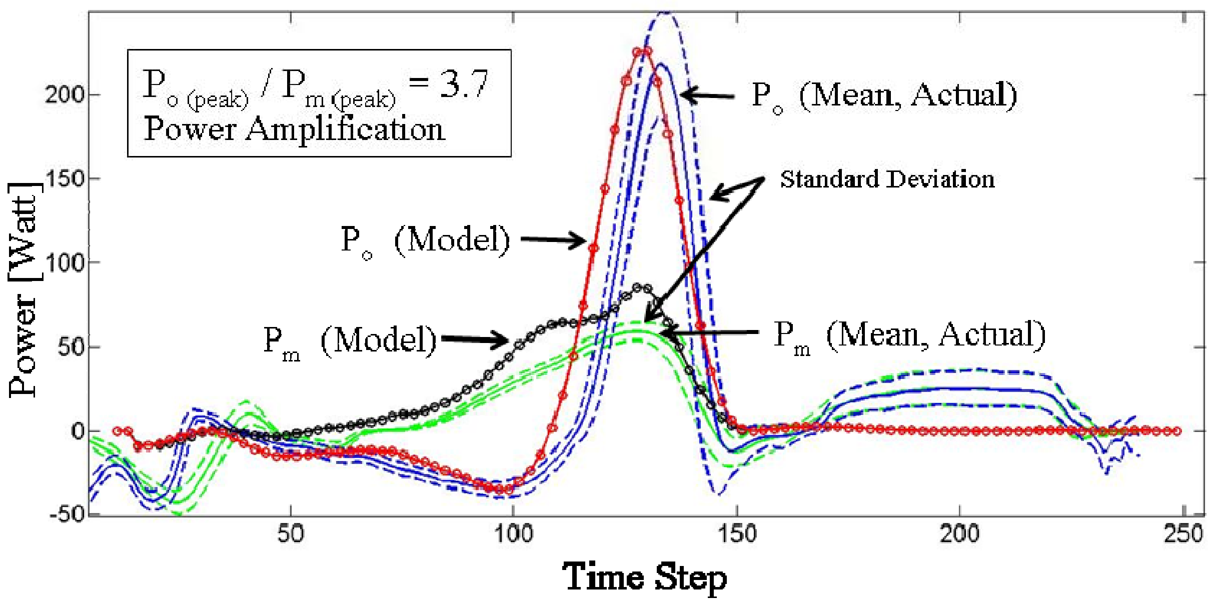



Figure 14: The subject walks at 2.2 mph. Measured power out, $P_o$, and power at the nut, $P_m$, for the test series with a 36KN/m spring and a 9 cm lever at 1 m/s (2.2 mph). The figure shows the mean and standard deviation of the data and its corresponding models, as annotated. Note that the device achieves a very high level of power amplification of 3.7. This is the unique advantage of a Robotic Tendon. A sophisticated model was built to simulate a gait cycle and the model data matches the mean data well.

Subject is walking at a very fast 3.7 mph on a treadmill with a powered prosthetic ankle. SPARKy is a lightweight, energy efficient, and powerful device using a tuned spring for a given body mass. At push off (frames 7, 8, and 9), the mechanical power out of the device is 3.7 times greater than mechanical power into the device. This boost in power is possible by storing energy in the stance phase (frames 2, 3, 4, 5, and 6). A spotter is holding a safety switch that can turn off the robot.

## Key Research Accomplishments:

Our powered ankle devices include the following characteristics:

- User has full range of sagittal ankle motion comparable to able-bodied gait. (23 degrees of plantar-flexion, 7 degrees of dorsiflexion.)
- User has 100% of the required power for gait delivered at the correct time and magnitude.
- The peak output power is 3-4 times larger than the peak motor power allowing a reduction in motor size and weight.
- Provide the user the flexibility to easily remove and install the Robotic Tendon to allow SPARKy to be used as a “powered and computer controlled” prosthesis or a “standard” keel and pylon prosthesis
- Based on lightweight, energy storing springs
- Allows a highly active amputee to regain high functionality and gait symmetry
- A demonstration of a powered, transtibial prosthesis was performed on November 2nd, 2007 at The Center for the Intrepid, Brooke Army Medical Center.

SPARKy’s biggest advantage lies in the fact that we are storing energy in a spring uniquely chosen for an individual. If one chooses the correct stiffness, the spring can be adjusted by the motor to allow for a 3 to 4 times power amplification. Because we have a large power amplification, we can use a small motor allowing a very large sized user to walk slow or walk at a very fast pace. Currently, we are only using 55 Watts of a 150 Watt motor so that we can easily power large individuals and can power fast walking.

We are using a fully intact keel that will absorb the heel strike impact and allow for correct rocker motion over the heel. The Robotic Tendon can be detachable so that it can be easily removed reverting back to a standard, passive carbon fiber keel. This feature can provide an alternative if the electronics fail in a field condition.

We are focused on developing the most durable, versatile, and powerful walk/run prosthetic ankle that meets the goals of a highly functional Military amputee. Because of our power amplification, we can easily walk very fast and have confidence in building a walk/run device for Year 3.

# Reportable Outcomes

- Manuscripts
  - one PhD dissertation,
  - one MS thesis
  - one conference paper was published
  - two journal papers were submitted

- Popular Press – multiple web pages and newspaper articles discussed research

- Presentations – presented research at Dynamic Walking 2008

- Demonstrations – Brooke Army Medical Center, Center for the Intrepid, November 2007

- Joseph Hitt earned his PhD in May 2008

- Ryan Bellman earned his MS in August 2008

# Conclusion

Significant advances have been achieved towards creating a computer-controlled, powered transtibial prosthesis that can actively support a user in their normal environment and conditions. Low power, high energy consumption, and sophisticated control methodology are key challenges towards realizing a smart, powered prosthesis. In Phase 1, the SPARKy project was able to develop a prosthesis that could supply high peak power to the user at push off in a light weight and energy efficient device.

The key outcomes included:

1. the user has full range of sagittal ankle motion comparable to able-bodied gait. (23 degrees of plantar-flexion, 7 degrees of dorsiflexion, and
2. the user has 100% of the required power for gait delivered at the correct time and magnitude.

The modeling, design, and testing of SPARKy Phase 1 were described in the body section of the report. The human subject test data shows that our approach gains kinetic advantages by storing energy in a uniquely tuned helical spring. The device provides the user 100% of the ankle power and ankle joint movement similar to able-bodied gait. This unique device is one of the most powerful and efficient devices of its kind.

The analyses and test data show that the peak motor power can be decreased while providing the user 100% of the required power. We showed a power amplification of the output powered compared to the input power of 3 to 4 times. This power amplification allows the downsizing of the actuator to a portable level. For example, a small 150 W motor in combination with a transmission and spring provides 200 W to 400 W during testing. This size and weight of the system is to a level that is comfortably portable to the user while powerful enough to support an 80 kg subject up to his maximum walking speed of 1.8 m/s (4 mph). The data suggests that there is enough power available to support even larger users at such speeds.

Finally, this project exceeded our expectations in terms of the device performance. New control methodology and embedded microprocessor control will allow our Phase 2 device to move from the laboratory to the unstructured and highly dynamic environments that include stairs, inclines/declines and over ground walking. These demands are very challenging but our successful Phase 1 research effort provides the team high confidence that such a device is possible.

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Joseph K. Hitt, Thomas G. Sugar, Matthew Holgate, and Ryan Bellman, "A Robotic Transtibial Prosthesis with Regenerative Kinetics: The Design Analyses and Methods, *submitted to* ASME Journal of Medical Devices.

Joseph K. Hitt, Matthew Holgate, Thomas G. Sugar, Ryan Bellman and Kevin W. Hollander, "Building an Energy Efficient Robotic Transtibial Prosthesis: The SPARKy (Spring Ankle with Regenerative Kinetics) Project, *submitted* to ASME Journal of Mechanisms and Robotics.

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**Thesis:**
Thesis: Mechanical and Conceptual Design of a Robotic Transtibial Prosthesis, Ryan Bellman, Arizona State University, August 2008.

# Appendices

A journal paper is attached that was *submitted* to the ASME Journal of Mechanisms and Robotics.

# Building an Energy Efficient Robotic Transtibial Prosthesis: The SPARKy (Spring Ankle with Regenerative Kinetics) Project

Joseph K. Hitt, Matthew Holgate, Ryan Bellman, Thomas G. Sugar and Kevin W. Hollander

***Abstract*—By applying "regenerative kinetics" the project seeks to develop a new generation of powered prostheses based on lightweight, uniquely-tuned, energy-storing elastic elements in series with optimal actuator elements that will significantly reduce the peak power requirement of the motor and the total system energy requirement while providing the amputee 100% of required "push-off" power and ankle sagittal plane range-of-motion comparable to able-bodied gait. This paper presents the design, the power and energy efficiency analyses, and the results of a 5 month trial using one below the knee amputee subject as part of the first phase of SPARKy, a multiphased project. This paper will present data to show that SPARKy Phase I provides full range of sagittal ankle motion and ankle power comparable to able-bodied gait. The data will show that by leveraging uniquely tuned springs and transmission mechanisms, motor power is easily amplified more than 4 fold and the electric energy requirement is cut in half compared with traditional approaches.**

## I. Introduction

This project is a multi-phased multi-year development effort. It seeks to tackle several leading technical challenges that prevent the development of a truly biomimetic foot-ankle prosthetic device. This includes (1) prohibitively low power and energy density in traditional actuation schemes, and (2) development of a control methodology that translates user intent into human like movement. Current state of the art portable devices cannot provide 100% of the power and ankle motion required in all ranges of walking gait.

There have been significant improvements in prosthetic and orthotic technologies in recent years. Several prosthetic companies have produced devices that are more comfortable, provide life-like cosmeses, provide significant energy return and are now even computer controlled. A world-class below the knee amputee sprinter using a high performance composite prosthesis can now sprint the 100 meters only one second off of the able-bodied world record [1]. Energy storage and return devices allow faster walking velocity and better terrain negotiation [2-4]. They have increased range of motion; they store and return energy; and they reduce the needed metabolic requirements [5-9]. Microprocessor controller components such as the Rheo Knee use artificial intelligence to change joint angles and dampen joint motion in response to the environment and individual gait style [10]. MIT's powered foot-ankle is a microcomputer controlled prosthesis that provides power and ankle motion at normal walking speeds with a maximum energy output of approximately 27 J/s [11].

Hydraulic, pneumatic, direct-drive, series-elastic, electroactive polymer-based, chemical-based and many other actuation schemes are also at varying stages of research and development. Other researchers are working on wearable robot control. From the highly publicized neuro-controlled bionic arm [12] to embedded gait pattern control [13], EMG motion control [14,15] and state based control [16] are all producing positive results. For example, the Proprio Ankle by Ossur is a commercially available state control device that modulates ankle angle based on the environment, gait and condition to better mimic the kinematics of the lost limb, however, without the functionality to actively generate power [17].

Again, even with these significant achievements, the current state of the art is far below what is required to support amputee gait that is comparable to able-bodied gait. This paper presents analyses and data to show that this project has achieved energy efficiency levels and power output levels beyond what is currently found in literature.

## II. Ankle Complex During Walking Gait

Gait is a cyclical pattern of leg and foot movement that creates locomotion. Gait is commonly discussed in terms of a percentage of a single gait cycle. A gait cycle is defined for a single leg and begins with the initial contact of the foot with the ground or 'heel strike'; the conclusion of a cycle occurs as the same foot makes a second 'heel strike'. To illustrate a typical pattern of gait, consider the illustration of the ankle complex during stance phase of a single cycle of gait, Fig. 1 and the kinematics and kinetics of a normal ankle, Fig. 2. Notice that in Fig. 2, peak ankle moment occurs at roughly 45% of the gait cycle and at a normalized value of -1.25 Nm/kg. The negative sign represents the physiological direction of the plantarflexing ankle. The foot rotates downwards to push off from the ground. At the point

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at which the peak moment occurs, the ankle angle begins a rapid decent to its lowest overall value of -24 degrees at 60% of the gait cycle. The region of gait approximately between 45% and 60% of the gait cycle is known as ‘push off’. At the conclusion of ‘push off’, now considered ‘toe off’, the leg initiates ‘swing’ and the foot is then positioned for the next ‘heel strike’.

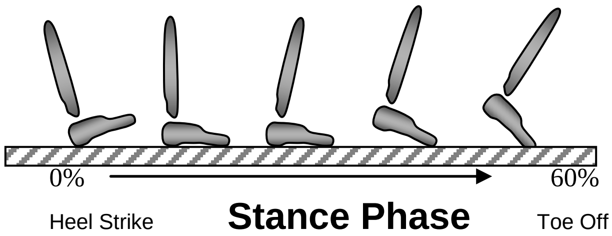


Fig. 1. Stance phase of a single gait cycle. 60-100% of gait is the swing phase, not shown.

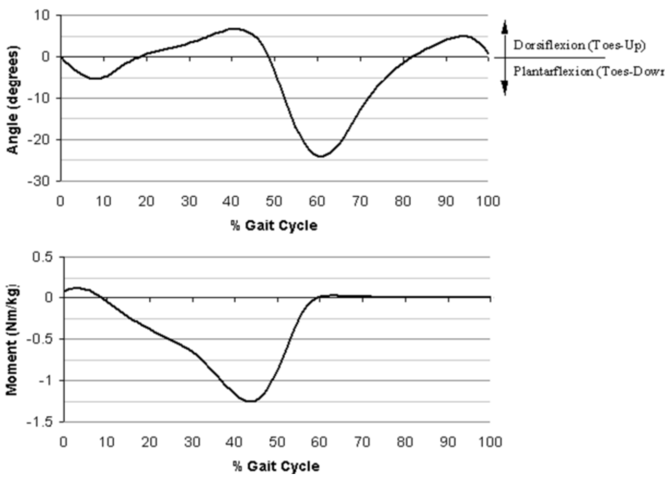


Fig. 2. Normal Ankle Gait: Kinematics and Kinetics [18].

## III. POWER AND ENERGY DENSITY

A portable, daily-use powered prosthesis such as SPARKy requires both high power to weight ratio (power density) and energy to weight ratio (energy density) in an actuator. Without these limitations, one could take, for example, a RE75 DC Motor from Maxon Precision Motors, Inc. rated for 250W continuous power to provide the 250W peak power required in human gait (80 kg subject at 0.8 Hz walking) [19]. But this motor in combination with a gearbox in a traditional direct drive approach would weigh 6-7 kg, which exceeds the weight of a typical biological below knee limb. Providing the idealized 36 Joules of energy per step [19] also becomes an issue because one must consider the efficiency of the motor, gearbox and other transmission mechanisms, friction and inertia, and the consumption of energy by the sensors and electronics. Just the mechanism inefficiency alone can double the energy requirement. For example, a DC motor with an average efficiency of 70%, connected to a ball screw at 90% and a gearbox at 80% multiply to produce a 50% efficiency actuation system. This would suggest a doubling of the energy input requirement to 72 Joules/step to provide the necessary 36 Joules/step at the output end. This is an optimistic estimate because this does not include several other factors such as: the energy consumed to counter motor/actuator inertia, which our tests show, is considerable in a highly cyclical gait pattern where the motor rapidly changes direction several times per step, friction in the mechanism or energy required by the microprocessor, sensors, motor controller, etc., Fig 3. One can easily see that actual energy requirement could grow to three or four fold of the idealized number of 36 J/step in a traditional approach and consequently growing the battery requirement proportionately and to non-portable levels. Also under these circumstances, slow running which may quadruple the peak power requirement as compared to normal walking (1000 Watts for heel to toe running as compared to 250 Watts for walking) would send power and energy density requirements beyond what can be achieved.

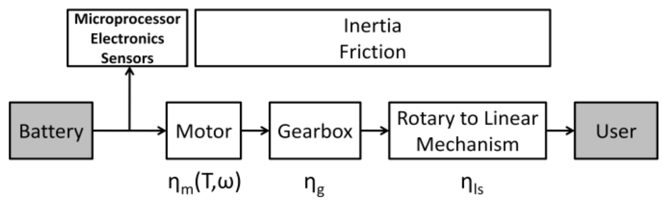


Fig. 3. This diagram illustrates the flow of power and energy from the battery to the user. Significant amount of energy is lost due to inefficiency in the mechanisms, motor, inertia, friction, etc. Proper selection and design can drastically improve overall system efficiency. Note the system efficiency is defined as average output power to the user/average input power from the battery.

## IV. REDUCING THE MOTOR POWER REQUIREMENT

SPARKy utilizes the Robotic Tendon [19] actuator to minimize the peak motor power requirement by correctly positioning a uniquely tuned helical spring so that the spring provides most of the peak power required for gait. The Robotic Tendon is a small and lightweight actuator that features a low energy motor that is used to adjust the position of the helical spring using a very simple position controller. Fig. 4 illustrates how the desired spring deflection and consequently via Hooke’s Law the desired force and ankle moment is achieved using a spring. As the ankle rotates over the foot during the stance phase as shown in Fig. 5, a lever position profile as shown in Fig. 4 is obtained. By correctly positioning the motor, a desired spring deflection as shown in the shaded area of Fig. 4 is obtained. A heavy, powerful, impedance controlled motor is not needed because the Robotic Tendon stores a portion of the stance phase kinetic energy and additional motor energy within the spring. The spring releases its stored energy to provide most of the peak power required during “push off.” Therefore, the power requirement on the motor is significantly reduced. As described in [19], peak motor power required is 77W compared to 250W for a direct drive system in the 80 kg subject at a 0.8 Hz example. Consequently, the weight of the Robotic Tendon, at just 0.95 kg, is 7 times less than an equivalent direct drive motor and gearbox system that is required to provide the necessary peak power. In other words, the Robotic Tendon achieves a

power density that in essence is 7 times greater than a traditional direct drive approach. Fig. 6, in comparison with Fig. 3, illustrates the addition of regenerative power and energy made possible with the spring in series with the motor.

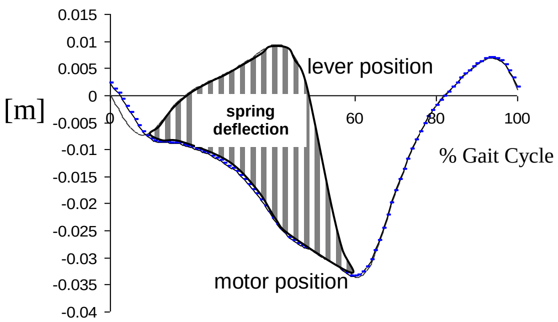


Fig. 4. Desired spring deflection, shaded area, is achieved by controlling the motor position and capitalizing on the cyclical nature of gait. As the tibia rotates over the stance foot, the lever extends the springs. Simultaneously, the motor extends the spring in the opposite direction to achieve the desired spring deflection and via Hooke's Law the forces required to generate the required ankle moment for walking.

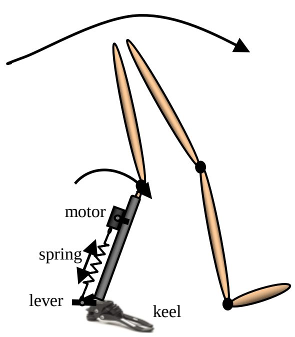


Fig. 5. The ankle rocker motion extends the spring. The motor increases the spring deflection to add additional energy into the spring to support push off. The spring provides the majority of the peak power required during push off.

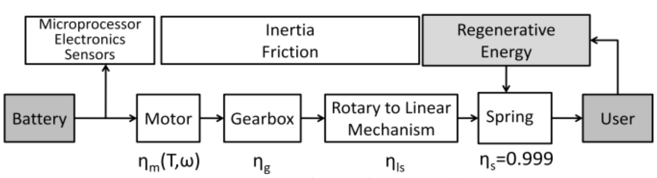


Fig. 6. This diagram illustrates the flow of energy from the battery to the user for the Robotic Tendon model. Even though significant amount of energy is lost due to inefficiency in the mechanisms, motor, inertia, friction, etc., the spring and the regenerative energy that it harnesses is nearly 100% efficient and accounts for the main share of the output energy. This method also allows for a smaller motor, battery and transmission system.

## V. REDUCING THE MOTOR ENERGY REQUIREMENT AND INCREASING EFFICIENCY

SPARKy increases energy density of the actuation system by using the spring, which is almost 100% efficient, to provide most of the energy. Additionally, ideal motor energy requirement, as determined by the integration of the power curves, is reduced from nearly 36 Joules in the 250W peak power case to 21 Joules per step in the 77W peak power case described above (80 kg subject walking at 0.8 Hz.) This significantly reduces the energy input burden of the motor and it allows the much more efficient helical spring to store and release energy.

Another significant aspect of energy density is motor efficiency. The RE40 DC Motor by Maxon, Inc. currently used in the Phase I SPARKy is one of the most efficient motors commercially available for this application. However, its rated efficiency of 90% is only achieved at a very small range of motor torque and rpm - near 7000 rpm at 0.1 Nm. Below 2000 rpm and above 0.2 Nm, motor efficiency quickly drops below 50%. The derivation of the ideal RE40 motor efficiency follows in the discussion and its 3D plot is shown in Fig. 7 as a function of motor torque and motor rpm. Motor properties such as torque and velocity constants used in the derivation are from Maxon Motor's published specifications [20].

$I_{nl} \equiv$ no load current $= 0.137$ Amp
$T_{max} \equiv$ stall torque $= 2.29$ Nm
$rpm_{max} \equiv$ max rpm $= 7580$ rpm
$kr \equiv$ speed constant $= 317$ rpm/volt
$kt \equiv$ torque constant $= 0.0302$ Nm/Amp
$R_m \equiv$ terminal motor resistance $= 0.317$ Ohm

Motor efficiency is Mechanical Power Out/Electrical Power In, equation (1):

$$E_m = \frac{\text{mechanical power}}{\text{electrical power}} = \frac{T\omega}{VI} \qquad (1)$$

Where $V$ is voltage in Volts, $I$ is current in Amps, $\omega$ is the angular velocity in radians/sec, and $T$ is torque in Nm.

A relationship between torque and motor current can be established using equation (2) and between rpm, current and motor voltage using equation (3):

$$I(T) = I_{nl} + \frac{T}{kt} \qquad (2)$$

$$V(rpm, I) = \frac{rpm}{kr} + R_m \times I \qquad (3)$$

Equations (2) and (3) provide an approximate voltage and current input requirement to the motor for a given mechanical power output. Therefore, by evaluating Equation (1) as a function of motor torque and angular velocity, one can determine the predicted motor efficiency.

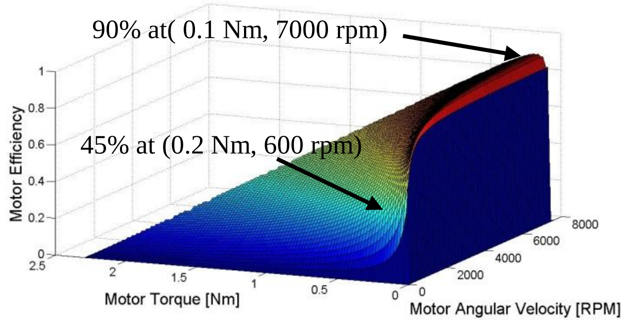


Fig. 7. 3D plot of the RE40 motor efficiency as a function of motor torque (Nm) and motor angular velocity (rpm). Notice that the highest efficiency of 90% is only achieved at a narrow range of torque and angular velocity. Operating the RE40 at speeds lower than 2000 rpm or torque above 0.2 Nm will significantly degrade the motor efficiency. Illustrated in the figure are two points on the mesh.

The 3D plot in Fig. 7 clearly shows that there is a narrow range of motor efficiency above 70%. Once the motor slows below 2000 rpm or motor torque exceeds 0.2 Nm, the motor efficiency degrades exponentially. Therefore, the motor should be properly matched with an appropriate gearing mechanism that maintains high motor speed and low torque.

On SPARKy Phase I, a 4.3 gear ratio gearbox from MAXON rated at 90% efficiency, ¼-16 ACME 4 start lead screw and an adjustable length lever are used to achieve high motor efficiency. A lead screw was selected over other rotation to translation mechanisms such as a ball screw or a roller screw for several reasons. A ball screw is highly efficient because of its rolling contact but is limited in terms of the dynamic load rating. Roller screws are also very efficient and they have high dynamic load ratings but the price can be prohibitive.

The efficiency of a typical lead screw is low compared to the other transmission mechanisms mentioned above. The efficiency of a lead screw is expressed in equation (4) [21], where $\mu$ is the friction coefficient and $\alpha$ is the lead angle:

$$\eta = \frac{1 - \mu \tan \alpha}{1 + \mu \cot \alpha} \tag{4}$$

By using a small diameter lead screw with a proportionately large lead, one can achieve a lead angle that allows for maximum efficiency. By selecting a lubricated steel lead screw and bronze nut, one can achieve a coefficient of friction below 0.1. The efficiency of our lead screw is above 0.7 as determined by the method outlined in [21].

## VI. SPARKY DESIGN

### A. Mechanical Design

The mechanical design of SPARKy has presented several obstacles that needed to be overcome to maximize the energy output without limiting the comfort, capability and safety of the robot. Fig. 8 shows two perspectives of the modeled prosthetic ankle. A new parallel two spring Robotic Tendon is attached to a custom aluminum pylon and to a commercial FS3000 Keel from Freedom Innovations via a lever. The three sensors that provide closed loop feedback are not shown in these illustrations. The computer and electronics are packaged in a portable 5” x 7” case worn in a fanny pack for the current phase of SPARKy I, Fig. 9.

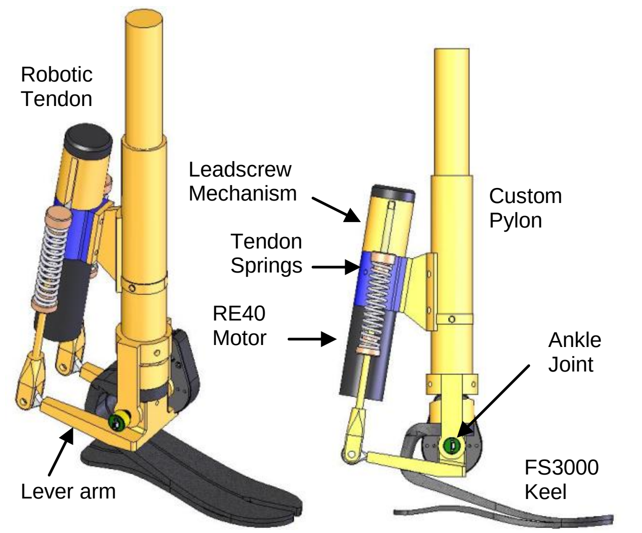


Fig. 8. Isometric and side views of current design as modeled in Solid Works. The RE40 motor coupled with the robotic tendon provide a dynamic moment about the ankle joint.


Fig. 9. The computer and electronics are packaged in a small portable package for this phase of SPARKy. SPARKy II will include a microprocessor and electronics embedded in the prosthesis.

For tuning purposes, there was also a great need for adjustability in many aspects of the design. As the spring stiffness requirement changes with the weight of the user, the system must incorporate interchangeability with springs. It was also desired that the lever arms have some level of adjustment, as a minute change in the length of the lever arm can have drastic effects on the power generation as discussed in the previous sections. This was done by using male threaded rod ends.

Future possibilities were also taken into consideration in this design. A common complaint by users of such prosthetics is the discomfort associated with stepping on a laterally slanted surface due to the rigidity of the keel in that dimension. While the split-keel design of this foot alleviates this to some extent, further advantage may be taken by the dual spring design of the robotic tendon. The current design has an additional axis in the ankle that allows for the springs to operate separately in the event of an ankle “roll,” allowing approximately 17 degrees in each direction. For phase 1,

however, this motion was further limited by rubber bushings on each side of the central shaft.

### *B. Electronics, Sensors and Computing*

SPARKy is controlled in real time using Real Time Workshop and Simulink from Mathworks. The Simulink model is compiled on to the embedded target PC running the xPC Target Operating System. An encoder at the motor, an encoder at the ankle joint and an optical switch embedded at the heel provides the necessary sensor feedback. Advantech's 650MHZ PC-104 with 512MB on board memory is selected to run the system. A multifunctional I/O board from Sensoray Co., Model 526, which is connected to the PC104 via an ISA bus, controls a RE-40 Maxon DC motor with encoder feedback. Future prototypes will make use of a computing system fully contained in the prosthesis.

### *C. Control*

Together with power and energy density, computer control of prostheses remains a significant challenge. Efforts towards control methodology that produce biologically realistic movement in prostheses and orthoses began in the early 1960s with work such as the Belgrade Hand. However, even after a half century of work, achieving human like control is proving to be very difficult. Work by Au et al and Ferris et al in EMG position control [14-15] and by Pappas et al in state based control [16] seems promising because of its simplicity. Sugar's effort to reduce the control problem using compliant simple force control [22] is a key finding towards simplifying control methodology and served as our starting point with the Robotic Tendon.

The SPARKy controller, as described in [23-24], has a predetermined gait pattern, which is based on able-bodied gait data from [18] and kinetic analysis from [19], expressed as a time-based function embedded in the controller, which drives the motor controller and thus the system. Gait is initiated at heel strike with activation of an optical switch embedded in the heel. As the user initiates gait, the motor drives the lead screw nut through a pattern predetermined for each subject with closed loop feedback. The ankle, however, is not forced to follow the specific pattern because the compliant spring is between the motor and user, safely absorbing environmental irregularities such as a rock under foot or user errors. This inherent compliance not only provides for a safer interface, but allows for a much simpler control scheme because high-bandwidth, high-precision force control is not required.

## VII. SPARKY MODELING

It is understood from a pogo stick and a hopping robot example that springs alone are not enough to provide 100% of the power required for its dynamic tasks. Motors alone are too expensive in terms of power and energy as discussed earlier. What combination of actuator, Robotic Tendon spring stiffness, ankle joint motion and control scheme is optimal? To answer these questions, multiple models were derived, each with varying combinations of these design parameters. Ankle joint angle and moment data used in the simulation are from able-bodied data generated by inverse dynamics of motion capture and force plate test data and published by Whittle in [18]. The remaining kinetic and kinematic analysis is derived using a quasi-static approach. MATLAB simulation of the models showed that a power amplification of up to 6 may be possible. Presented here is one of those models selected for SPARKy Phase 1 for its simplicity and robustness in terms of mechanical design and control. Simulation of this model showed that a power amplification of more than three is possible while maintaining gait kinematics and kinetics similar to able-bodied persons.

In the simple series model, the keel and the Robotic Tendon springs are in series, therefore, the moment in the keel is equal to the moment in the Robotic Tendon. Motor position is controlled so that the moment of the Robotic Tendon matches that of the able-bodied moment data, Equation (5). Note that $K_a$ is the keel stiffness in N/m, $K_s$ is the spring stiffness in N/m, B is the radius of the keel deflection in meters, d is the moment arm due to the keel deflection in meters, and $l$ is the lever length in meters. See Fig. 10.

$$M_A(t) = M_{keel}(t) = M_{RT}(t) \qquad (5)$$

$$\begin{aligned} &\textit{where}: \\ &M_A \ \textit{from published AB data} \ [18] \\ &M_{keel}(t) = -K_a B d \varphi(t) \\ &M_{RT}(t) = K_s(x(t) - l\theta(t))l \end{aligned}$$

Solving Equation (5) for motor position, x(t), determines the expression in Equation (6):

$$x(t) = l\theta(t) - \frac{K_a B d}{K_s l}\varphi(t) \qquad (6)$$

The assumed force in the Robotic Tendon is given by Equation (6):

$$F(t) = \frac{M_A(t)}{l} \qquad (7)$$

The ideal power generated by the motor to move to position x(t) is given by the product of the force and velocity in the tendon, Equation (8):

$$\begin{aligned} &P_m(t) = F(t)\ \frac{dx(t)}{dt} \\ &\Rightarrow P_m(t) = \frac{M_A(t)}{l}\left[ l\,\frac{d\theta(t)}{dt} - \frac{K_a B d}{K_s l}\,\frac{d\varphi(t)}{dt} \right] \qquad (8) \end{aligned}$$

The expression in Equation (8) represents the power required by the motor to generate the desired moment and ankle angle of able-bodied gait published in [18] given that the spring provides majority of the required peak power.

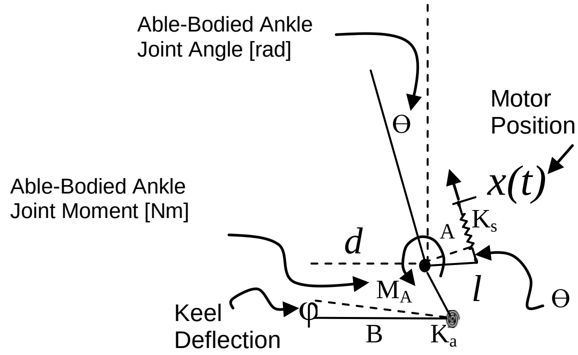


Fig. 10. A 2 degrees-of-freedom model with a seismic excitation representing the motor excitation, a torsional spring for the keel and a helical spring between the lever and the motor is shown. The moment due to the keel is a function of $\varphi(t)$ and the moment due to the spring is a function of $x(t)$-$l\Theta(t)$. The moment at the ankle is from published information determined using inverse dynamics of motion capture and force plate test data as published in [18].

Optimization of Equation (8) varying keel stiffness, $K_a$, and spring stiffness, $K_s$, showed that a minimum peak motor power profile is achieved by varying $K_s$ as seen in Figure 11. This figure is a surface plot of the peak power at a given spring and keel stiffness. It shows that a spring stiffness of 32000N/m is optimal in terms of minimum peak motor power. At this spring stiffness, the peak motor power is at its lowest value of 80W. Note that as the tendon spring becomes rigid, required motor power reaches that of a direct drive system. As the tendon spring stiffness reaches zero, required motor power becomes asymptotically large.

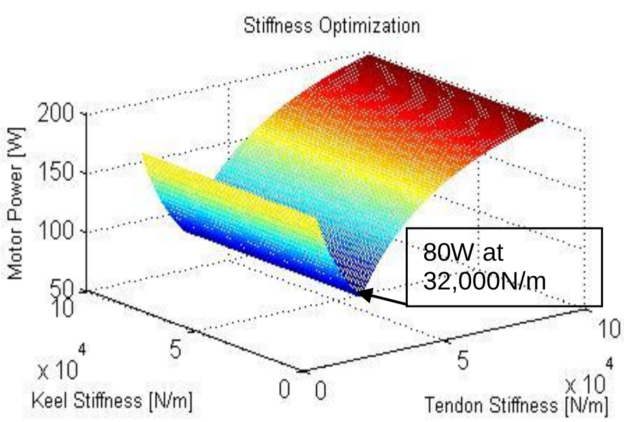


Fig. 11. A surface plot of the peak power from Equation (8) varying $K_a$ and $K_s$. Notice that at a spring stiffness of 32,000 N/m, the minimum peak motor power of 80W is achieved. Keel stiffness does not greatly influence the design in this optimization.

The results are significant because it shows that SPARKy with use of a keel and Robotic Tendon can achieve significant kinetic advantages. With an input power of 80W from the motor, this simulation illustrates that SPARKy, with use of springs, can deliver the required 260W of peak gait power, which is a power amplification of 3.25. Fig. 12, generated from the simulation, shows the motor, gait and keel power profiles. Notice that the motor power peaks at 80W and the gait power peaks at 260W. The keel power profile is not additive because the system is in series. However, notice that this power profile is similar to what is found in literature describing the power of energy storage and return (ESAR) keels.

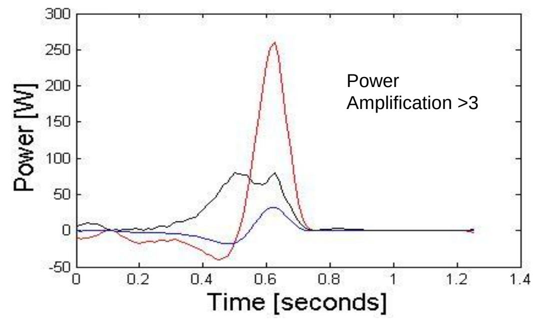


Fig. 12. The power profiles for able-bodied gait (system output power) in red, required motor power in black and power from the keel in blue. (From simulations.)

This series model achieves 100% of the required peak gait power with less than a third of the peak input power (motor power) by harnessing the energy storage potential of springs. In addition, because the system's joint motion is controlled only by the counter-moments of the tendon spring and keel, kinematics of the system is almost identical to the desired able-bodied gait, see Fig. 13. Note that the ankle joint motion is identical to the desired able-bodied ankle angle data as seen in Fig. 2 and total motion of the ankle-foot complex is the summation of the ankle joint motion and keel deflection. This total motion of SPARKy provides its user with kinematics similar to able-bodied gait kinematics representing a significant improvement from today's state of the art.

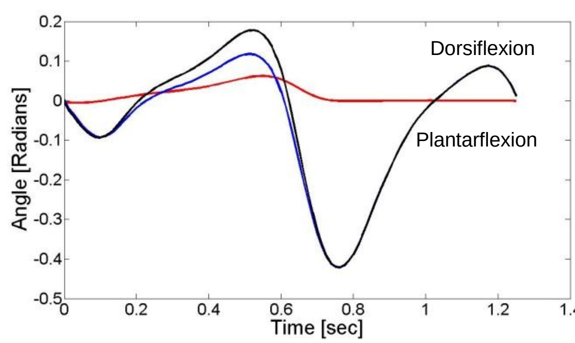


Fig. 13. The ankle joint angle is shown in blue; the keel deflection angle is shown in red, and the sum of both angles is shown in black. (From simulations.)

## VIII. SPARKY TESTING

SPARKy Phase I device was tested on a single transtibial amputee male subject for a period of five months walking on a treadmill. Embedded sensor data such as motor and ankle encoder information was recorded at varying walking speeds with varying spring stiffnesses, lever lengths, and loading condition. In addition direct measurements of motor current and voltage information were recorded. This information was used to determine the ankle kinematics and kinetics of the user on the SPARKy device. Fig. 14 is a picture of a

transtibial amputee test subject, 80kg, walking over level ground using SPARKy.

Fig. 14. A picture of a transtibial amputee using SPARKy overground.

Fig. 15 shows the desired ankle position in red as modeled previously and the actual ankle position measured using the ankle encoder in blue. Testing clearly shows that SPARKy achieves full ankle sagittal plane range of motion. This finding is very unique because no other passive device can achieve this range of motion and there may be no other powered foot-ankle prosthesis that can achieve full range of motion at all normal walking speeds up to 2 m/s.

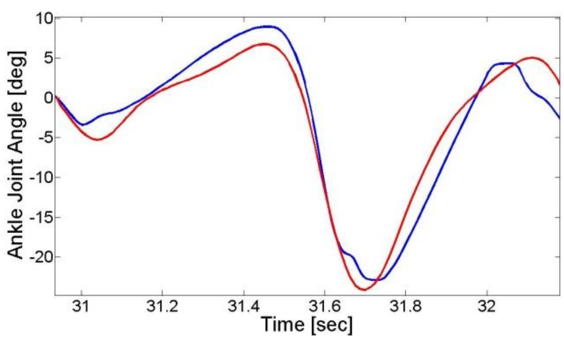


Fig. 15. The desired ankle movement is shown in red and the actual ankle movement is shown in blue for one walking gait cycle. The subject was walking at 0.98 m/s (2.2 mph) on a treadmill.

Fig. 16 shows the desired motor and gait (output) powers determined from our simple series model described earlier in purple and red, respectively. Using measured spring deflection to determine the force at the spring and ankle and motor encoder information to determine the velocity at the motor and at the ankle, motor and output powers are determined using the product of force and velocity. The blue line is the measured motor power and the green line is the measured output power. The measured powers are in very good agreement with the modeled powers. Fig. 17 shows the measured motor power in blue and the measured output power in green for a series of 9 gait cycles of our subject walking at 3mph. The power amplification is consistently above 4.5 (Peak Output Power/Peak Motor Power). The motor only outputs 60W peak but SPARKy with the use of springs delivers 270W of peak power to the user. Fig. 18 shows the measured power from the motor and spring. Notice that the spring provides the majority of the power required during push-off. This is very significant because this is what allows such high power amplification and consequently reduction in motor size and electric energy requirement.

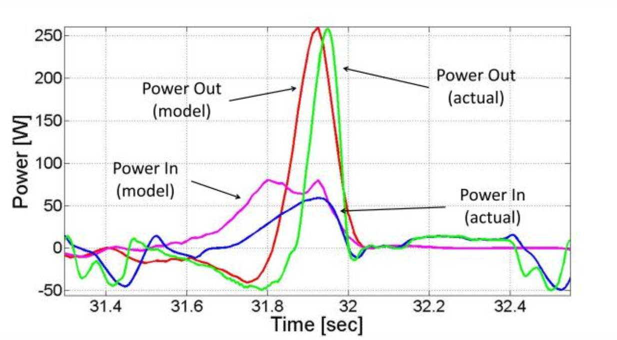


Fig. 16. The ideal output and motor power determined by the simple series model, shown in red and purple, respectively, vs. the measured output and motor power, shown in green and blue, respectively.

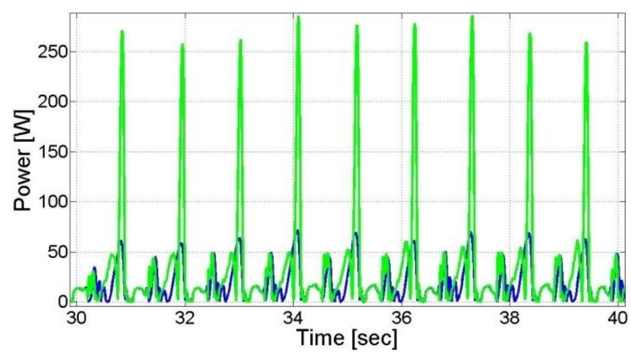


Fig. 17. The measured motor power shown in blue and output power shown in green for 9 gait cycles. Note that the power amplification is consistently above 4.5 (270W peak/60W peak). (Our test data has shown amplifications of 6 and 8 are possible.)

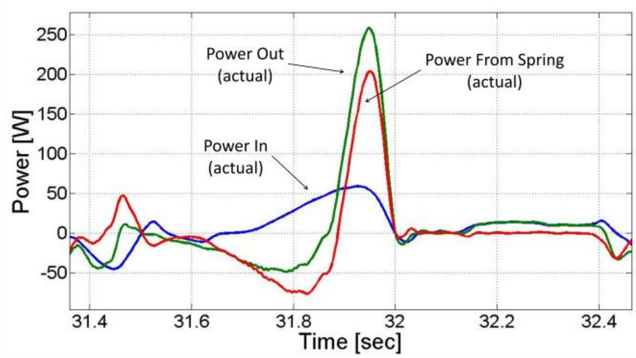


Fig. 18. The motor power shown in blue and the spring power shown in red sum to the output power in green. Note that the spring provides the majority of the push-off power required in gait.

Electric power used by the motor is determined using the direct measurement of current and voltage to the motor, blue line in Fig. 19. Integration of the electric power provides the energy input requirement for SPARKy at 1.3 m/s (3mph) as 43 J/s or 43W. Output power is the product of the measured ankle velocity and force. It is the green line in Fig. 19. Integration of the output power provides the energy output by SPARKy at 1.3 m/s (3mph) as 35 J/s or 35W. Therefore,

the system efficiency in terms of average power in and out is 35W/43W=0.81. This level of efficiency is only possible because majority of the work is done by the spring which is nearly 100% efficient. We have similar data and results with the subject walking at 0.5, 1, 1.3 and 1.8 m/s.

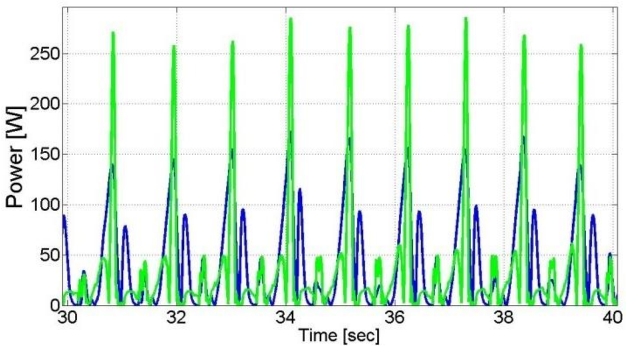


Fig. 19. The blue line is the electric power input as determined by the measured current and voltage to the motor. The green line is the same output power shown in Fig. 17.

## IX. Future Studies

SPARKy Phase I is complete and the team is currently working to design the Phase II system. The objective of the second year includes overground walking and robust, embedded microprocessor control. SPARKy II will feature a completely new control scheme and sensor suite that will allow continuous update of gait input based on measured user gait kinematics and kinetics. The design will include highly efficient brushless motors, two degrees of freedom (frontal and sagittal plane), and a much smaller form and half the weight of SPARKy I. SPARKy II will include functionality for various overground conditions and will better mimic human ankle motion with its additional powered degree of freedom in the frontal plane. This will allow for powered inversion and eversion which we hope will better support lateral motion. Fig. 20 shows the evolution in design from left to right SPARKy Ia, which is the current prototype, SPARKy Ib, which is an interim solution, to SPARKy II on the right. SPARKy II should be fully functional by late 2008.

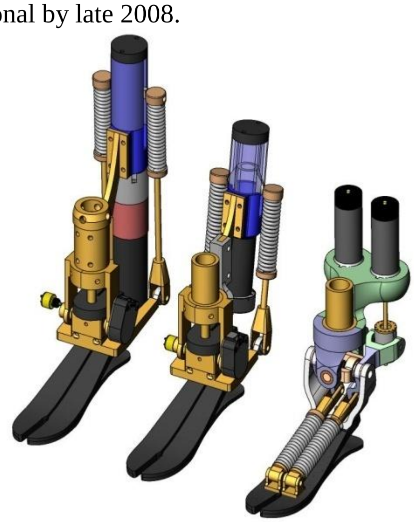

Fig. 20. From left to right are: SPARKy Ia, current prototype, SPARKy Ib, an interim solution, and SPARKy II, the end state prototype for Phase II.

## X. Conclusion

Significant advances have been achieved towards computer controlled active transtibial prosthetic devices that can actively support its users in their normal environment and conditions. The Proprio Ankle [17] by Ossur and the MIT's Powered Ankle-Foot Prosthesis [11] are good examples of the most recent achievements. We presented in this paper the design, analysis and testing of the Phase I SPARKy. We showed that our approach gains kinetic advantages by leveraging elastic energy potential in uniquely tuned helical springs. As the tibia rotates over the stance foot ankle during walking gait, we position the spring to maximize elastic energy storage. We presented the synergistic benefits of the Robotic Tendon in terms of motor efficiency and power and energy reductions. We presented test data to show that we achieved a power amplification of 4.5 consistently with the motor providing a peak of 60W and the spring providing the remaining 210W so that the user had a peak of 270W at push off while walking at 1.3 m/s (3mph). We showed that the system is 81% efficient in terms of the average electric power in to the motor (43W) and average mechanical power out to the user (35W). This incredibly high level of efficiency is only possible because the springs, nearly 100% efficient, perform majority of the work. We also show that SPARKy can provide 100% of the push-off power required in walking gait while maintaining gait kinematics similar to able-bodied gait. This is an unprecedented finding because this level of kinetic and kinematic performance may represent the very best in today's transtibial prostheses. Also, as significant is that this level of power amplification and energy efficiency brings highly efficient and portable powered running devices within sight. Additional details on the initial design and analysis of SPARKy can be found in [25].

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